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FIBER OPTIC WAVELENGTH DIVISION MULTIPLEXING: PRINCIPLES AND APPLICATIONS IN TELECOMMUNICATIONS AND SPECTROSCOPY

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Abstract

Wavelength Division Multiplexers have been established as a viable technology in telecommunications. These devices are based on optical fiber inputs and outputs of fixed wavelength and can be uni-directional or bi-directional. Design and fabrication tradeoffs are discussed and performance parameters with detailed data are given. The same multiplexer construction based on prism gratings has been used in spectroscopic applications, in the wavelength region from 450 to 1600nm. For shorter wavelengths down to 200nm a similar instrument based on larger fibers (500-1000u) has been constructed and tested with both a fiber array and a photo-diode detector array at the output.

Introduction

Wavelength division multiplexing has been shown in recent years to be a viable approach to increasing the transmission capacity of fiber-optic communication links. The advantage offered by a dispersive component (i.e. prism grating) over some of the other WDM methods is a high channel capacity which avoids all cummulative losses. The use of a quarter pitch graded index rod as shown in figure 1 results in a fully integrated device which is both compact and rugged, having no exposed optical interfaces which can become damaged [Erdmann et al., 1983]. This paper concentrates on the GRINrod-prism grating approach with emphasis on test methods, design parameters, fabrication techniques, as well as telecommunications and spectroscopic applications.

Fabrication Techniques

Prism Gratings

Dispersion of the channel wavelengths in the WDM is accomplished by a prism with a grating replicated to the hypotenuse as shown in figure 2. Fabrication is begun by mounting the prisms in a larger block substrate. A grating is selected and given a non-adherent vacuum deposited gold coating which gives the internal grooves of the replica prism their optimum reflectivity for the wavelength region of interest. Transparent epoxy is applied between the grating and the prism substrate, cured, and the prism separated and cut to final dimensions. The replication process utilized at PTR has been perfected by many years of grating production and results in replicas with efficiency and resolution equal to the original, thereby avoiding losses reported by some other groups. Note

also that the prism grating-GRINrod combination has the desireable properties of satisfying the quarter pitch condition while using the grating in collimated light [Erdmann et al., 1983].

Fiber Arrays Using V-groove Spacers

Precise alignment of the input and output fibers is accomplished by use of the v-groove spacers illustrated in figure 3. A precision ruling engine at PTR permits the manufacture of grooves in metal substrates controlled for shape and position to within several millionths of an inch. The first type is a series of right angle grooves, yielding either an array of adjacent fibers, or one with a regular separation for lower crosstalk. Other types feature independently controlled grooves as shown in figure 4. Each groove is tailored to fiber dimensions, and spaced to give an output at a specifically selected wavelength. Successful devices incorporating these spacers show good theoretical agreement with expected performance values [Metcalf et al., 1981]. This degree of easy wavelength selectivity greatly aids system design, since available sources are still evolving toward true wavelength selection control [Erdmann et al., 1983].

GRINrod

The quarter pitch GRINrod acts as both a collimating and refocusing lens to illuminate a Littrow mounted grating in collimated light. An input fiber source located on the entrance face produces wavelength dispersed return light for output fibers whose wavelengths are a function of position on the same face.

Construction of the device is illustrated in figure 5. This entails insertion of the fibers into the v-groove spacer, after which they are polished to a .3u finish at the spacer face to create the linear fiber array. The GRIN lens is cured to the prism-grating with UV-curing epoxy, after which the opposite lense face is aligned to the fiber array. Positioning along three translational axes and one rotational axis produces optimal output signal at the desired wavelengths.

Design

The design equation for the general prism grating device shown in figure 6 is:

$$\text{Eq. 1)}\quad d\lambda/dx = n_o \sqrt{a}\ d \cos[\theta - \sqrt{a}\ (n_e/n_p)X_o]$$

where:

X_o = Input fiber distance from lens axis
x = Radial distance from GRIN lens axis
n_o, n_p, n_e: Indeces of selfoc lens core, prism, epoxy
a = Quadratic index coefficient
d = grating spacing
λ = wavelength
θ = Prism angle

Thus, to find the spectral channel spacing for any physical separation we use:

$$S = (d\lambda/dx)(\Delta x)$$

where Δx = separation of fiber centers. This can take on any value greater than the core diameter (but may also be less than the cladding diameter via acid etching of the fiber [Hegarty et al., 1984]) and is restricted on the high side by the off-axis abberations in the selfoc lens. X_o can be chosen as zero at lens center to simplify calculations:

$$\text{Then Eq. 2)} \quad S = n_o\sqrt{a}\ d(\Delta x)\cos\theta$$

Example

A design with a fairly typical multimode spacing is detailed in the following. The application requirements are for a four output channel system equally spaced using only one LED covering 800-900nm. The MUX provides the channel wavelengths and the DeMUX is provided with a photodiode detector at each output fiber. The crosstalk limit of 30dB with <3dB average insertion loss is desired. The requirement is therefore: (900-800)/(4-1) = 33nm spacing

What needs to be calculated is Δx for given fiber dimensions. "$\sqrt{a}$ " is approximately 0.1 for 5mm lenses and .2 for 3mm. "d" is generally a standard spacing of 300, 600, 1200, or 1800 l/mm. Cosθ is found from the grating equation in a media of index N:

$$\sin\theta = \lambda/2Nd = 0.850um/[(2)(1.55)(0.833um)] = 0.329, \quad \cos\theta = 0.944$$

A) Using the 3mm lens in Eq. 2, and assuming the 125/50u trunk fiber restriction, a possible solution at 1200 l/mm (d=0.833um) yields Δx=135.3um.

B) The channel bandwidth is estimated from the ratio of the core diameter to the channel fiber separation, which for the 1200 l/mm case gives about 12.2 nm. The results of an actual device of this configuration (actual Δx=140um) are shown in figure 7 and correlate well with expected values.

C) The crosstalk can be predicted from the spectral profile of an individual channel (also fig. 7). An analysis of channel "1" shows that for this fiber type, a separation of ≃90um or more is required to give 30 dB isolation from the center of the adjacent channel, which is the case.

Efficiency/Performance

Various WDM applications have differing constraints and performance requirements. Insertion loss in a de-multiplexer, for example, can be reduced by using a smaller input fiber to

feed a larger output fiber. This is because of some inherent enlargement of the refocused image. In fact recent progress in laser diode control and coupling to single mode fibers with 1 to 10um cores makes this a promising area for WDM investigation. Other current applications require symmetric size compatability with existing fiber installations such as the standard 50 micron core telecommunication type. GRINrods are limited to 1 to 5mm diameters, with .1 being the smallest available value of $\sqrt{a}$, and gratings are usually available only in standard spacings, which are multiples or divisors of 600 l/mm. The last two conditions, together with fiber size, set definite limits for all cases on the total channel number, as well as channel spacing. The blaze angle of the grating is chosen, and the prism angle fabricated to optimize efficiency in the required wavelength interval (devices with <1.5dB insertion loss have been constructed). The use of a computer-aided calculation of the position equations completes the design and determines the required fiber separation and location prior to final alignment and assembly [Erdmann et al., 1983].

Efficiency Testing of the Demultiplexer

In order to test crosstalk and efficiency of prism-gratings prior to final cementing, one device has been constructed to serve as a MUX-DeMUX test station with two fibers mounted independently on precision stages. One becomes the input and the other is scanned through the array of output positions with throughput data taken as a function of position. Data is ratioed against a reference mirror, to extract insertion loss and crosstalk values. A "dry ice" and resistance heater temperature drift test was also performed in conjunction with the test station to examine wavelength stability and changes in refractive index, as well as overall survival limits. Material data so far shows that during temperature excursions of $-75\,^{\circ}C$ to $+100\,^{\circ}C$ (or more, as limited by the melting point of the UV epoxy), channel wavelenghts shift approximately +/-1nm.

W.D.M. in Telecommunications

Wavelength division multiplexing in telecommunications, by effectively providing multiple transmission lines through a single optical fiber, has established itself as a viable and cost effective technology. The lower losses of improved fibers (approx 1dB/km and .01dB/km single mode) and particularly the increased availability of controlled sources (both light emitting diodes (LED) and laser diodes (LD)) have stimulated the need for multiplexing devices in the .7 to 1.6um region. Frequency division multiplexing (FDM) is an alternative using electronic methods to multiplex signals, analogous to FM radio tuning, but the required equipment is substantially larger and more expensive. Various WDM designs have been demonstrated by different groups, most based on wavelength separation by means of optical filters or some type of diffraction grating as shown in figure 8 [Erdmann, 1986].

This paper concentrates on the prism-grating selfoc lens type because a grating-based device has the advantage of diffracting all wavelengths simultaneously and with nearly equal efficiency. This generally makes it preferable in practice to filter-based designs for any device with more than two channels. The selfoc lenses (from NSG) provide convenient focusing and together with the PTR array spacers and prism-gratings result in an ultra-compact solid state construction. The complete device is on the order of and inch long and a quarter of an inch in diameter. The advantage of the prism-grating compared with other grating devices is the modular design flexibility; all of the required components are readily available and can be matched on the basis of known performance characteristics [Aoyama et al., 1979]. They can in fact, be obtained in kit form. The results are source match compatible WDM devices which are not laboratory demonstration models but rugged practical devices provided in any quantity to order or as off the shelf models [Erdmann, 1986].

There are two main types of WDM applications sharing similar components. In passive multiplexing, independent wavelength sources, usually laser diodes, are modulated by a signal transducer and combined by the MUX and sorted again at the DeMUX stage. In one active type of multiplexing the MUX takes in light from a single broadband source, such as an LED, and produces distinct wavelength channels at each fiber. These signals can then be modulated and combined by the same device and transmitted via the trunk fiber to a DeMUX. Still other types with small multiwavelength sources require only a de-multiplexer. In general, minimizing coupling losses in a unidirectional system requires input fibers to have a core dimension equal to or smaller than the ouput core connection. The MUX fiber pigtails are therefore the same as the trunk fiber while the ouput fibers on the DeMUX may be larger to further minimize device losses due to any increase in refocused spot size [Erdmann, 1986].

Performance Data

Several traces have been provided to illustrate data taken from a selection of W.D.M.'s made to various specifications and implemented in functioning networks. Figure 9 shows a four channel standard item in the 850nmn window. Insertion losses are only 1.5 to 2.0dB and 30dB crosstalk isolation is acheived. Table 1 gives the specifications of a 6 channel MUX-DeMUX pair made for the 1300nm region. Finally, figure 10 shows corrected data on an all single mode 16 channel experimantal device.

Single mode devices are designed and constructed in essentially the same manner as multimode devices, but for a multiplexer the accuracy requirements are about an order of magnitude more critical and internal wavefront deviations on the order of $\lambda/4$ enlarge the refocused spot size increasing the insertion loss. For a DeMUX with multimode outputs, these constraints do not apply and the losses are always lower. The measured losses in figure 11 showed an 8dB average, but the

data curve is corrected for the bandpass of the test monochromator being twice the 2nm bandwidth of the device. The spectral broadening of the curves is due to the same phenomenon. Further tests with laser sources are planned to aid in the optimization of insertion losses at various wavelengths [Erdmann, 1986].

The above examples illustrate that even with the design restrictions imposed by the equations, a variety of WDM's with different performance requirements are currently being designed and produced and many others are possible. In summary, the properties of prism grating-based devices can be calculated and designs chosen according to the component parameters [Erdmann,1986] .

Spectroscopic Applications

The development of fiber optics and multiplexing technology in recent years has stimulated applications interest in spectroscopic fields. Since the devices themselves are essentially miniature fixed-wavelength monochromators, it is natural to explore their use in absorbance, reflectance and flourescence measurements. The convenient all fiber light transfer, small size alnd low cost motivate testing of performance limits. The first is insertion loss, not only in the device, but also at the source to fiber coupling. Larger fibers obviously help the situation, with up to 200um being practical in a prism grating device. Another solution is the use of a laser source such as and argon ion or recently available low cost tunable dye lasers.

A spectral reflectometer multiplexer is illustrated in figure 11. The entire optical system has no air gap interfaces or alignment requirements and detection can be done either with individual photo-diodes or a detector array. Figure 12 shows a flourescent scattering application and figure 13 displays the size scale and channel wavelengths. In this particualar experiment, the exciting line at 488nm made two passes through the device so the sampling fiber doubled as the flourescence signal collection fiber. It should be noted that any of the fibers could be chosen as the sample fiber resulting in only a wavelength shift of the other channels making its potential use even more versatile. The application was a Ph sensor with the sample retained on the surface of a porous glass bead [Erdmann, 1986].

Figure 14 shows florescein peaks and valleys distinguishing between normal and atherosclerotic artery tissue [Feld et al., 1985] . A MUX device was constructed with channels designed to perform at the appropriate curve peak and valley wavelengths. One constraint in such an application is the need to minimize interchannel stray light because of the small flourescence signal as compared to the intense excitation line. Several discrimination schemes can be utilized. A bandpass interference filter is either placed in sequence at the end of each fiber

channel, or integrated in the detector package. Similarly, a cascaded type multiplexer could act as a double monochromator theoretically giving the combined product of the signal-to-noise ratios. Figure 15 shows data taken through a channel with and without a cascaded stage. The measurements confirm the expected reduction of off band signal, but further work is required particularly at shorter wavelengths [Erdmann, 1986].

To test the effective limits of selfoc lenses at shorter wavelengths, a 550nm quarter pitch lens was mirror coated at one end. An adjacent input-output fiber pair was aligned at the opposite face to produce a reflection measurement through the lens (see figure 16). The fiber throughput and aluminum mirror reflection were normalized so that figure 17 represents the comparative lens losses as a function of wavelength. The indications are that for UV wavelengths another type of grating device, such as a planar waveguide, may avoid the restriction of the selfoc lens [Erdmann, 1986].

Fiber Optic Spectrograph (figure 18)

For use in the ultraviolet wavelength range another fiber-based device has been developed. The two problems with the above mentioned devices are the current limitations of the gradient lenses below about 450nm and the difficulty of focusing enough UV energy onto a fiber core of only 100 microns or less. The device is larger with dimensions of several inches and is intended for use with 400 micron core silica fiber. Two configurations are in use, one having a fiber array at the ouput and the other having a 35 element photodiode array at the exit plane. Compact size, low production cost, and simultaneous wavelength data acquisition capability are the main features of the spectrograph. The input in the second option can even be modified to accomodate a vertical fiber array allowing multiple sample analysis with the addition of a timed chopper mechanism [Erdmann, 1986]. In a typical configuration with the detector array the performance parameters are:

F#: 2.5
Insertion Loss: ≃8dB
Resolution: ≃ 1nm
Grating: 1200 l/mm
Wavelength Channels: 35
Input Fiber: 400u core

Conclusion

The prism grating-GRINrod combination is an effective approach to WDM as a result of the compact size and design flexibility of the prism grating, in conjunction with ruled spacer arrays. These components allow the manufacture of practical systems compatible with the current state of fibers and sources for communications. In addition, the devices have also demonstrated effective use in spectroscopic-diagnostic instrument applications. Clearly both areas will continue to

benefit as more applications are found for these ultra-compact, flexible devices.

References

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TABLE 1. Six Channel Multiplexer Typical Specifications

	Specification
Number of Wavelength Channels	6
Wavelengths	1220,1240,1260,1280,1300,1320nm
Channel Wavelength Spacing	20nm
Center Wavelength Tol.	+/- 2nm
Insertion Loss	4.0 dB
Isolation	-25 dB minimum
Interface	Fiber Optic Pigtail
Mode of Operation	Unidirectional
Laser Spectral Width	3nm FWHM
Input Fiber Size	50/125um, .2NA
Output Fiber Size	50/125um, .2NA
Channel Width (1dB down from peak)	4nm min.

As in [Erdmann, 1986].

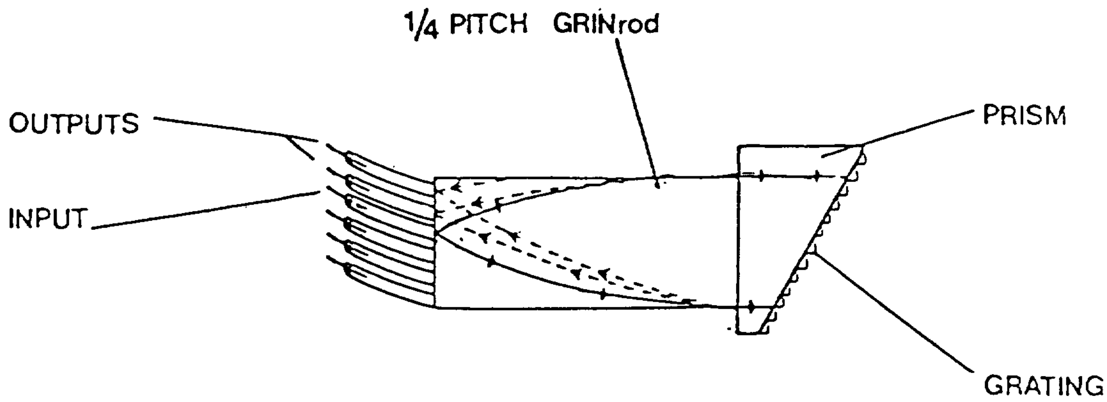

Figure 1.

Wavelength Division Multiplexer Configuration and Optical Diagram

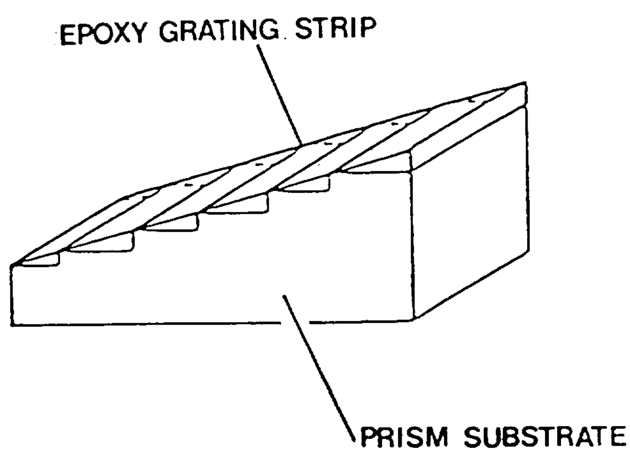

Figure 2.

Replicated Prism Grating

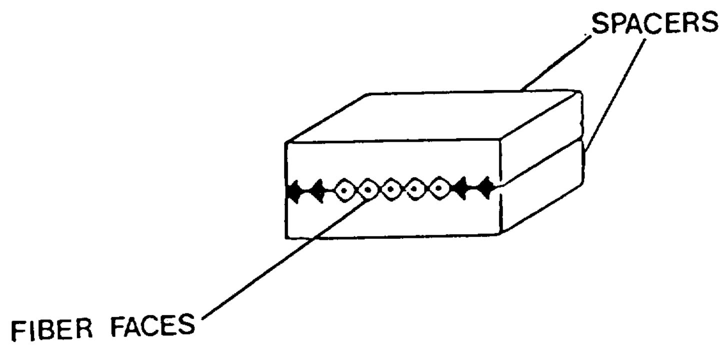

Figure 3.
Adjacent Fiber Array Using V-groove Spacers

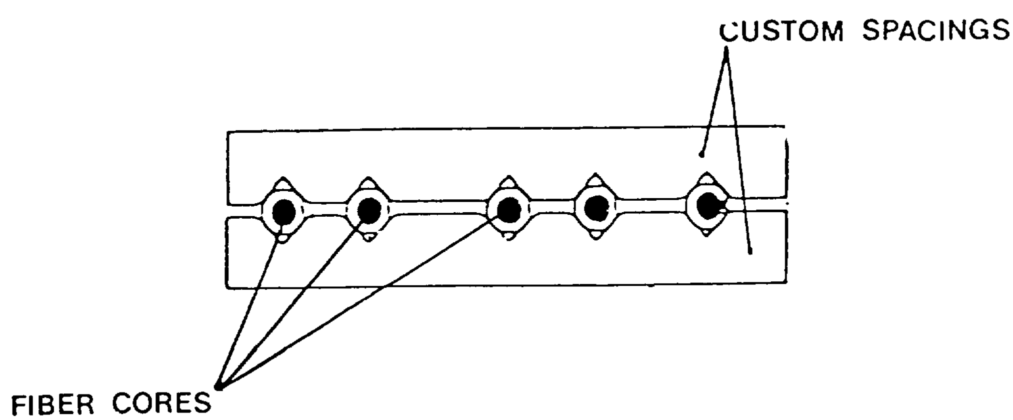

Figure 4.
Custom Fiber Alignment Using V-groove Spacers

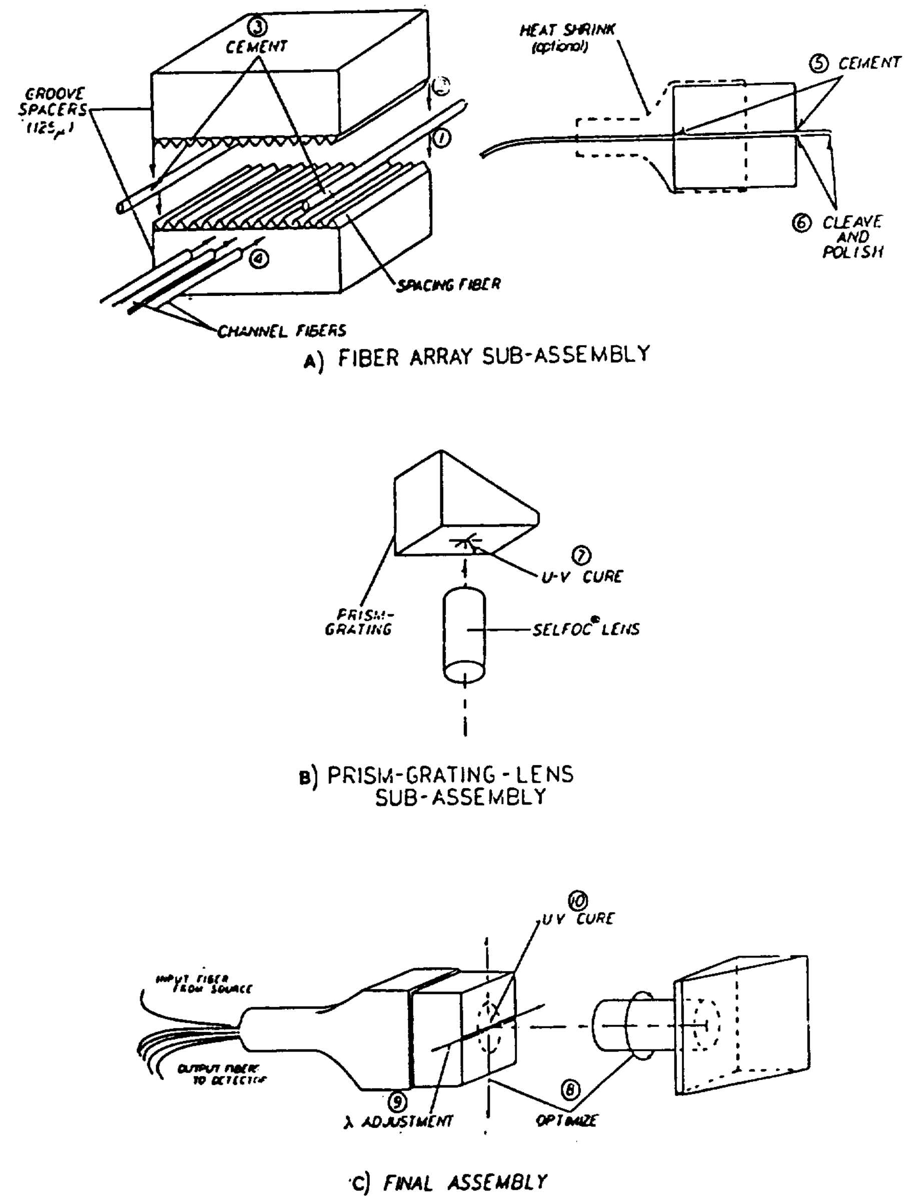

Figure 5.

Wavelength Division Multiplexer Construction
A) Fiber array sub assembly. B) Prism grating-lens sub assembly C) Final Assembly

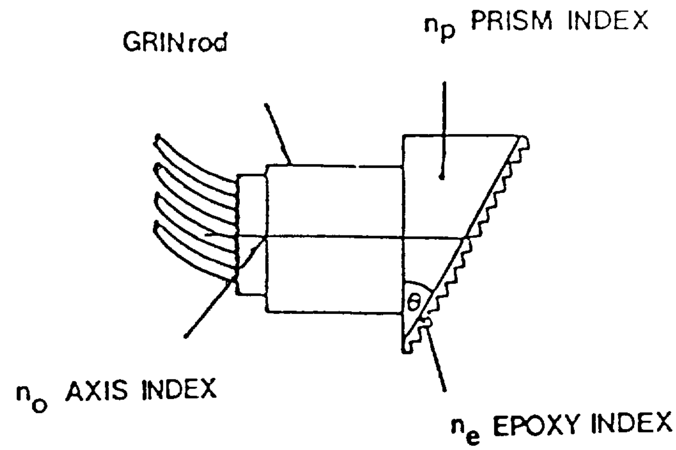

Figure 6.
General Prism-grating Multiplexer Component Indeces

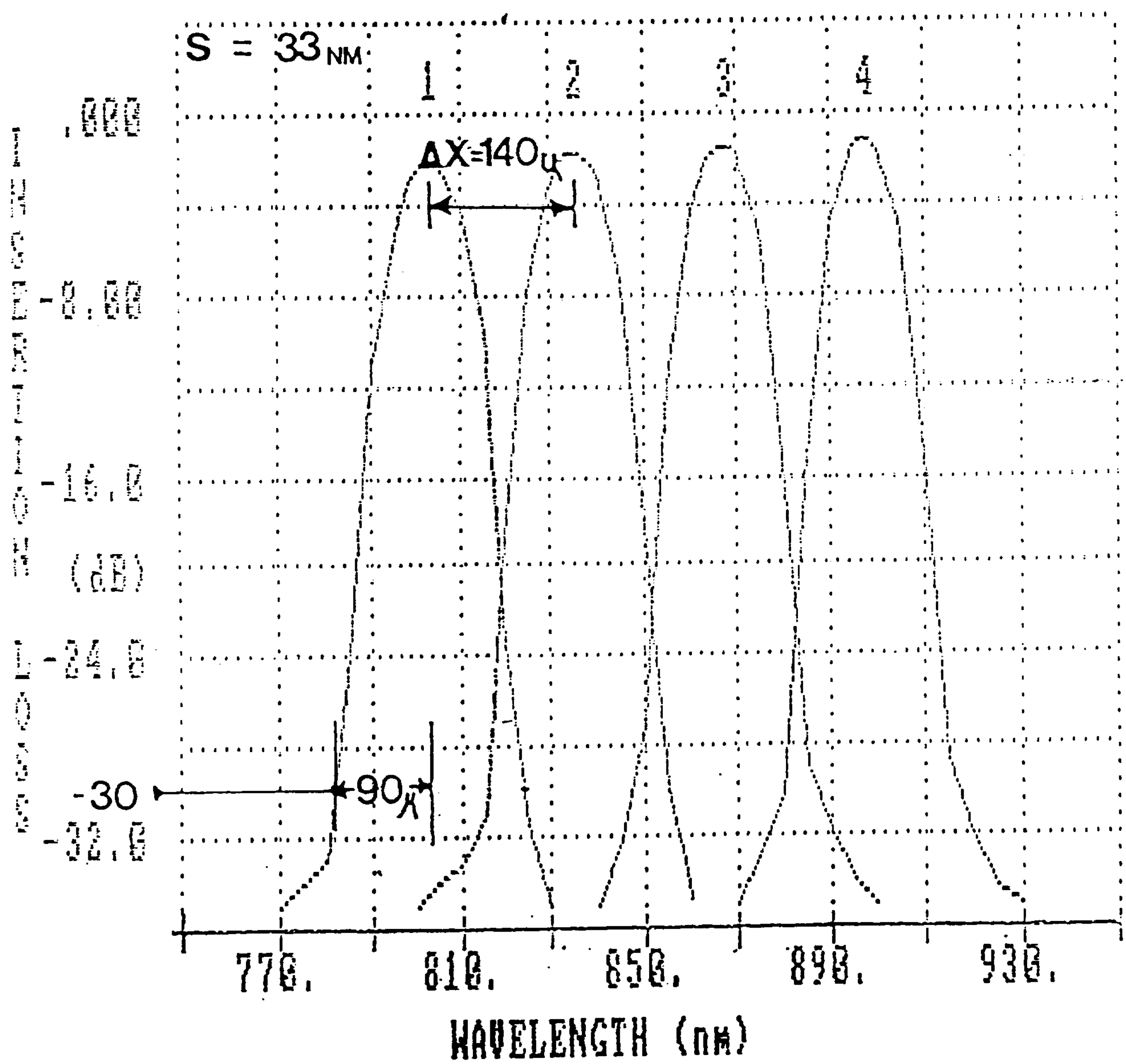

Figure 7.
Wavelength Division Multiplexer Design Example Results

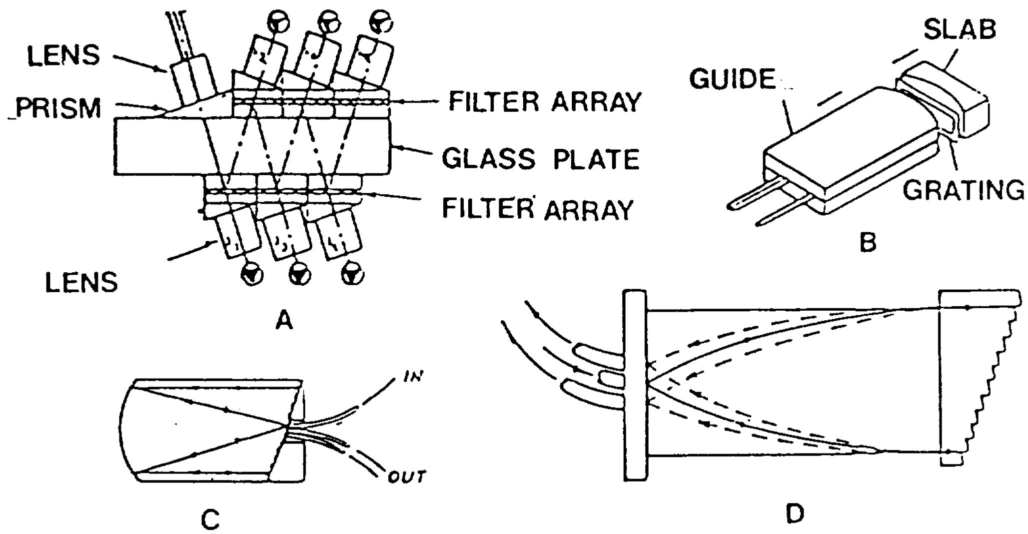

Figure 8.

W.D.M. Telecommunications Device Examples

A) Dichroic filter type. B) Slab-waveguide with grating C) Littrow type with concave mirror. D) Prism grating/ rod lens assembly

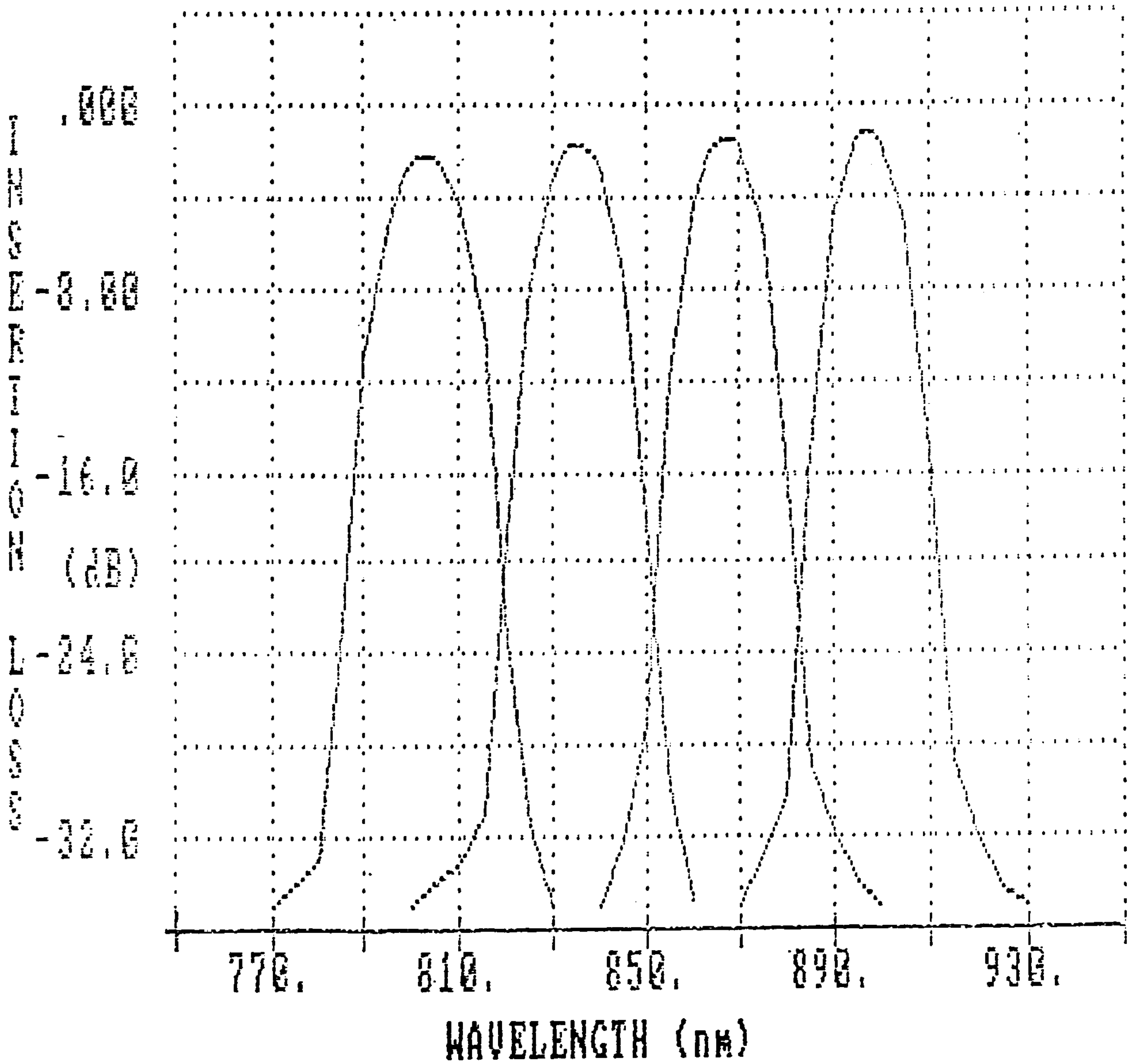

Figure 9.
Typical Four-channel standard W.D.M. Performance

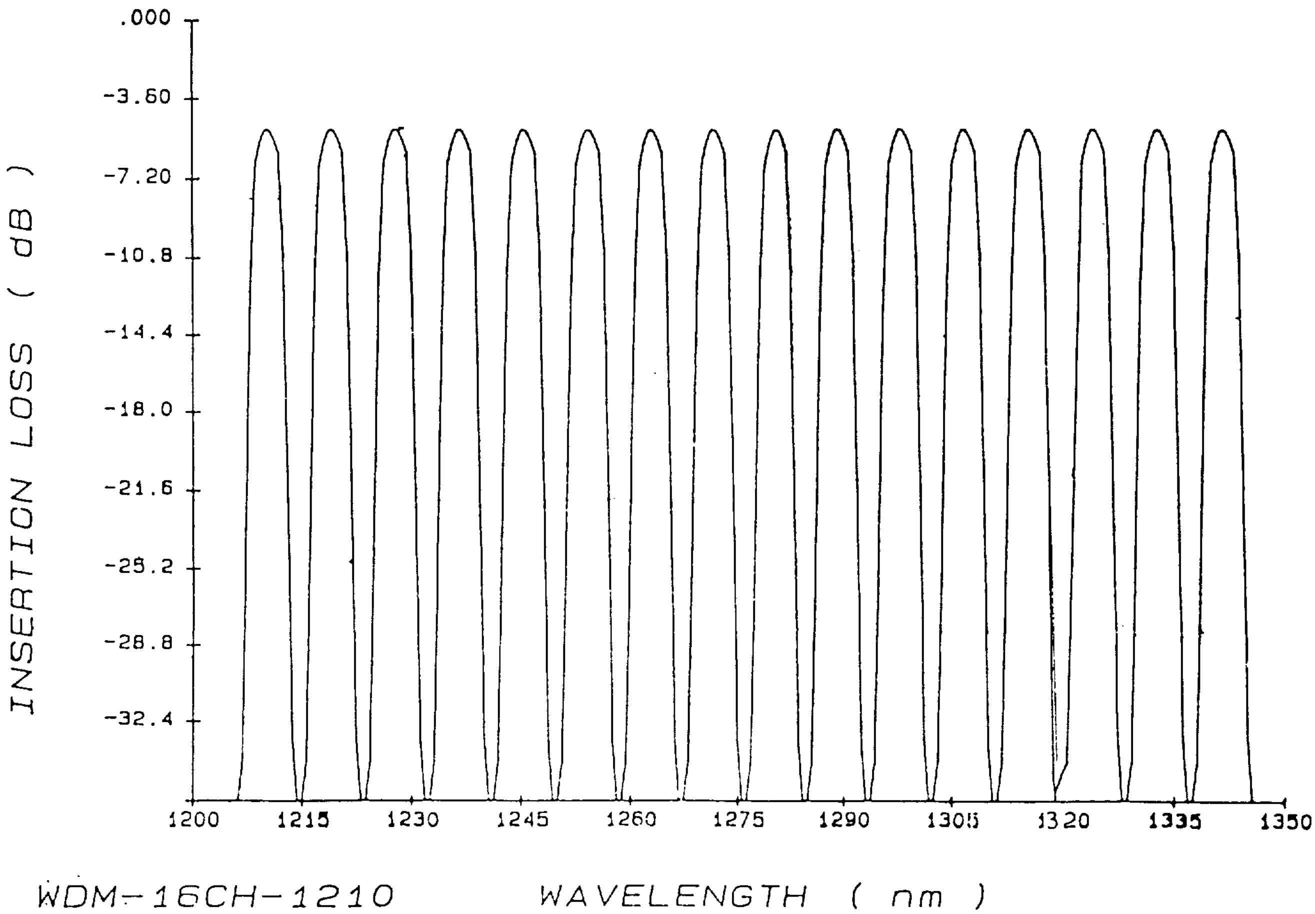

Figure 10.

Single Mode W.D.M. Typical Performance

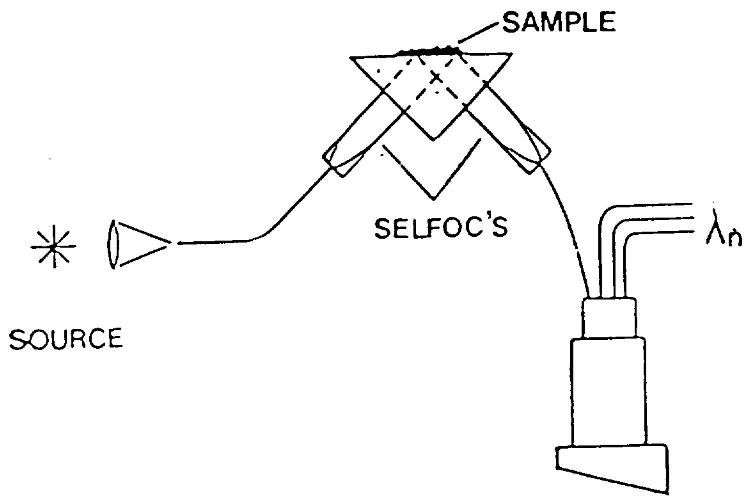

Figure 11.
Spectral Reflectometer Configuration

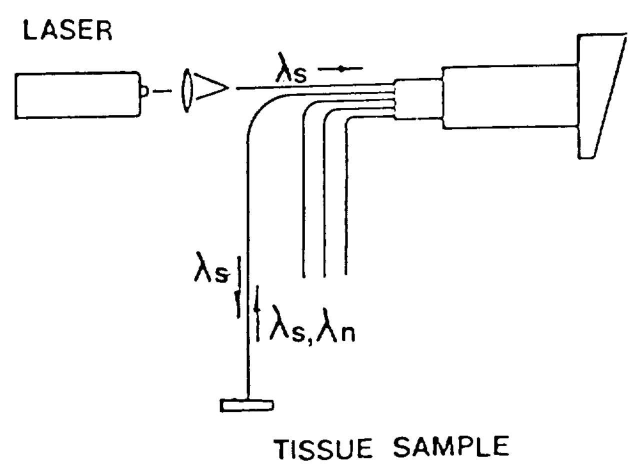

Figure 12.
Flourescent Scattering Measurement Configuration

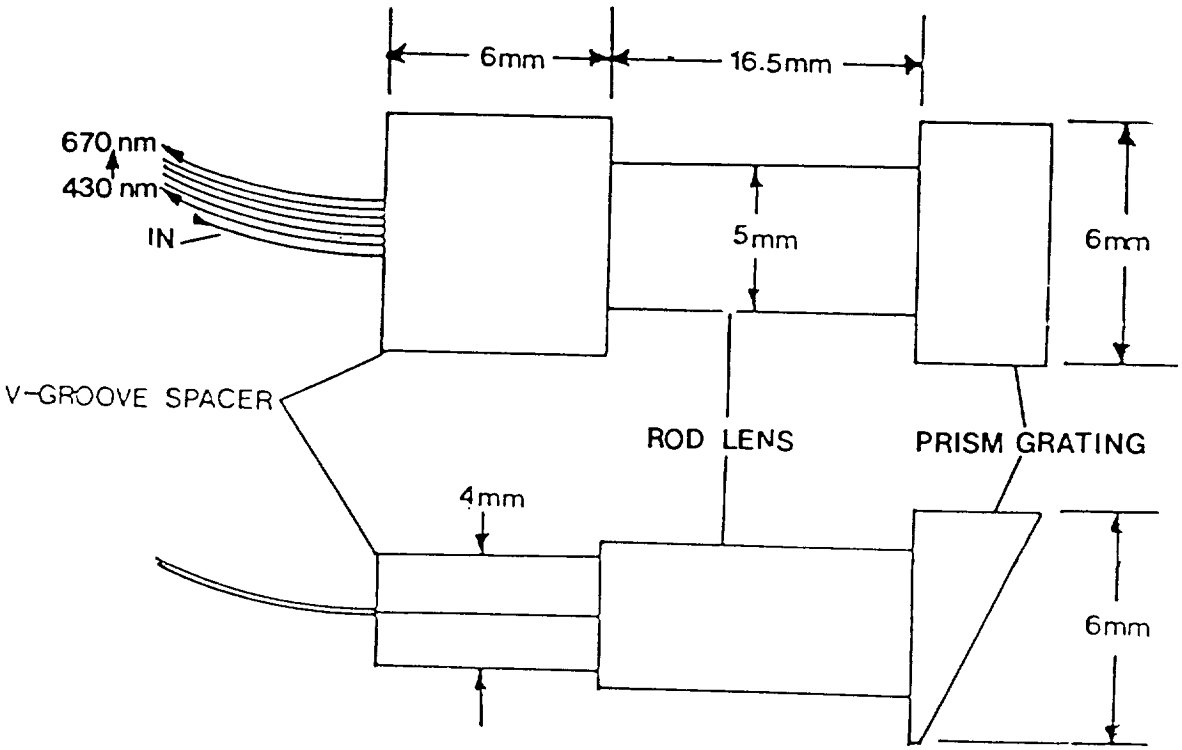

Figure 13.
Spectroscopic W.D.M. Dimensions and Sample Wavelengths

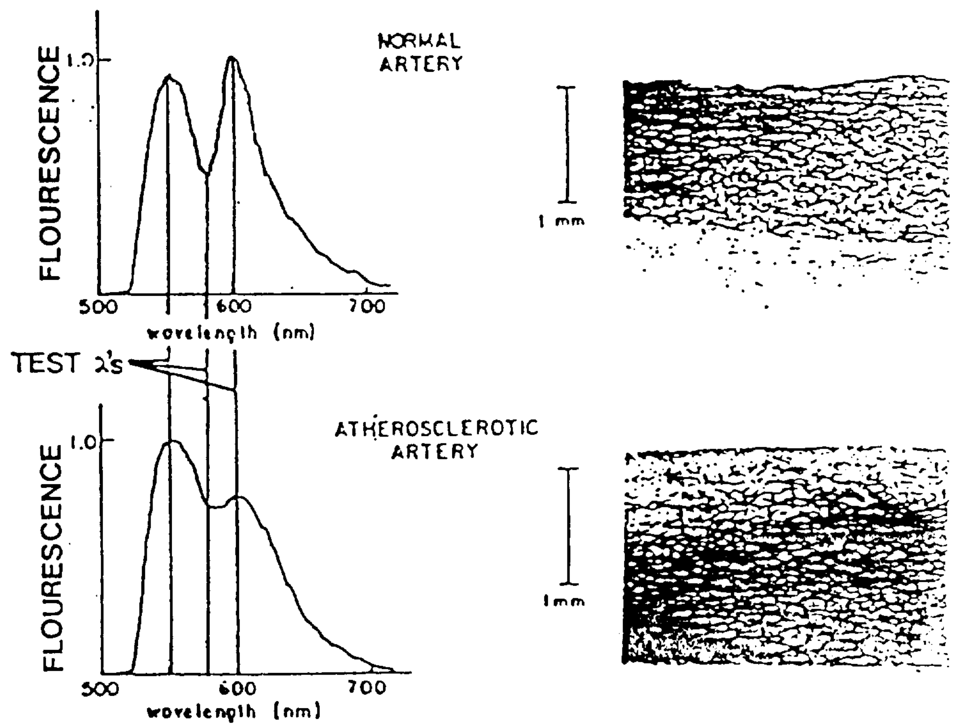

Figure 14.

Spectroscopic Analysis of Atherosclerotic Tissue

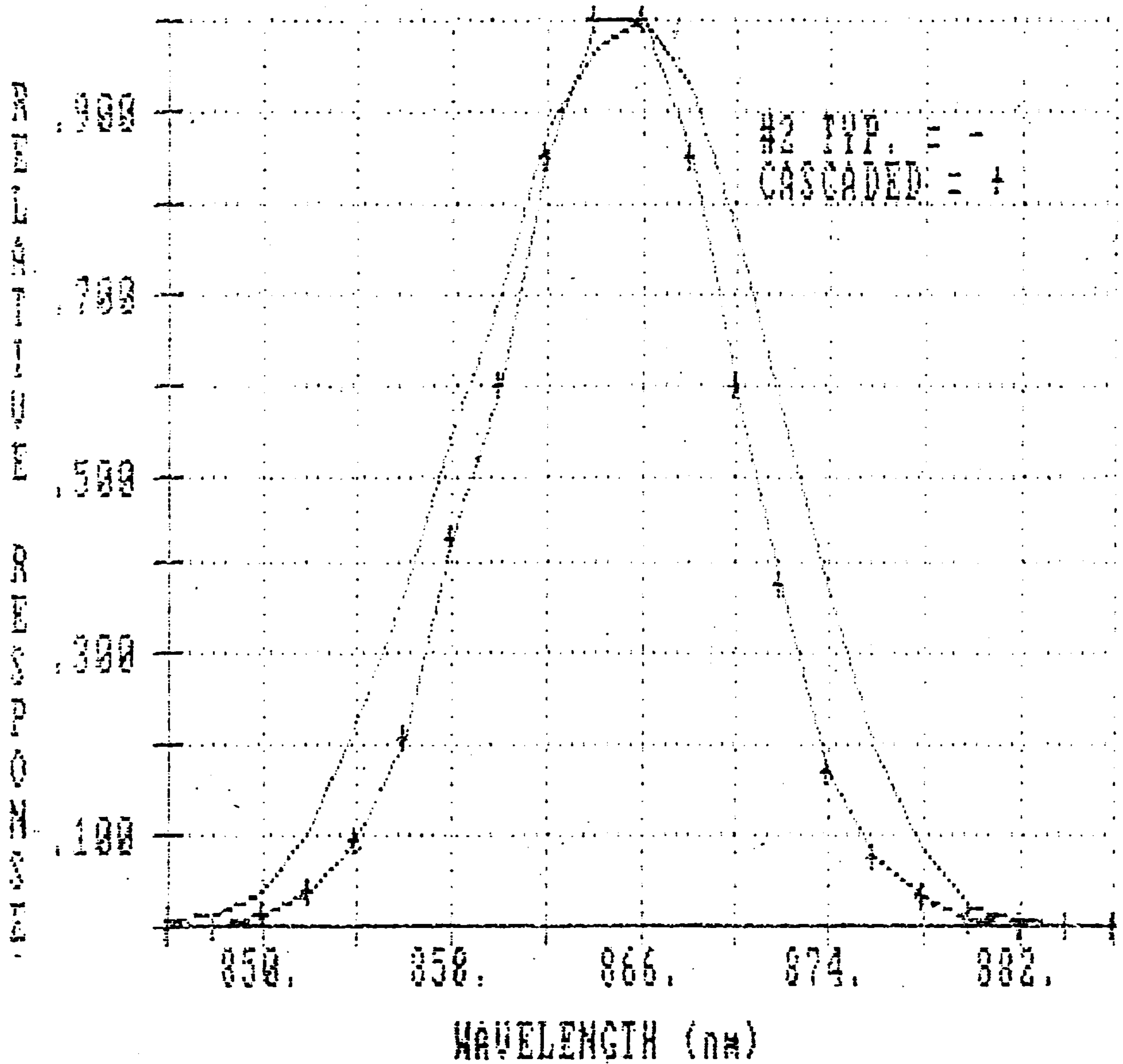

Figure 15.
Cascaded W.D.M. Bandpass Narrowing

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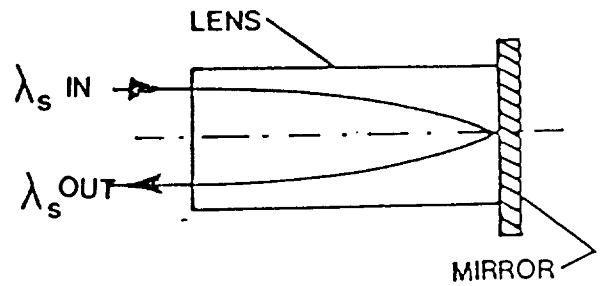

Figure 16.
GRINrod Loss vs. Wavelength Performance Test Configuration

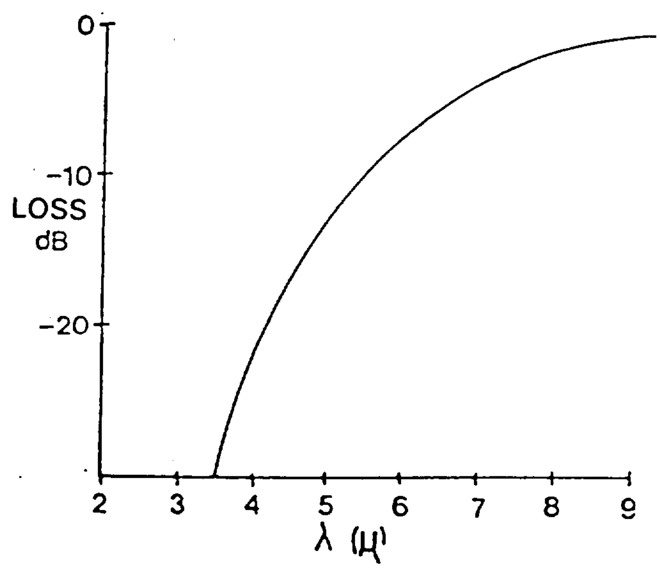

Figure 17.
GRINrod Loss vs. Wavelength Performance Test Results

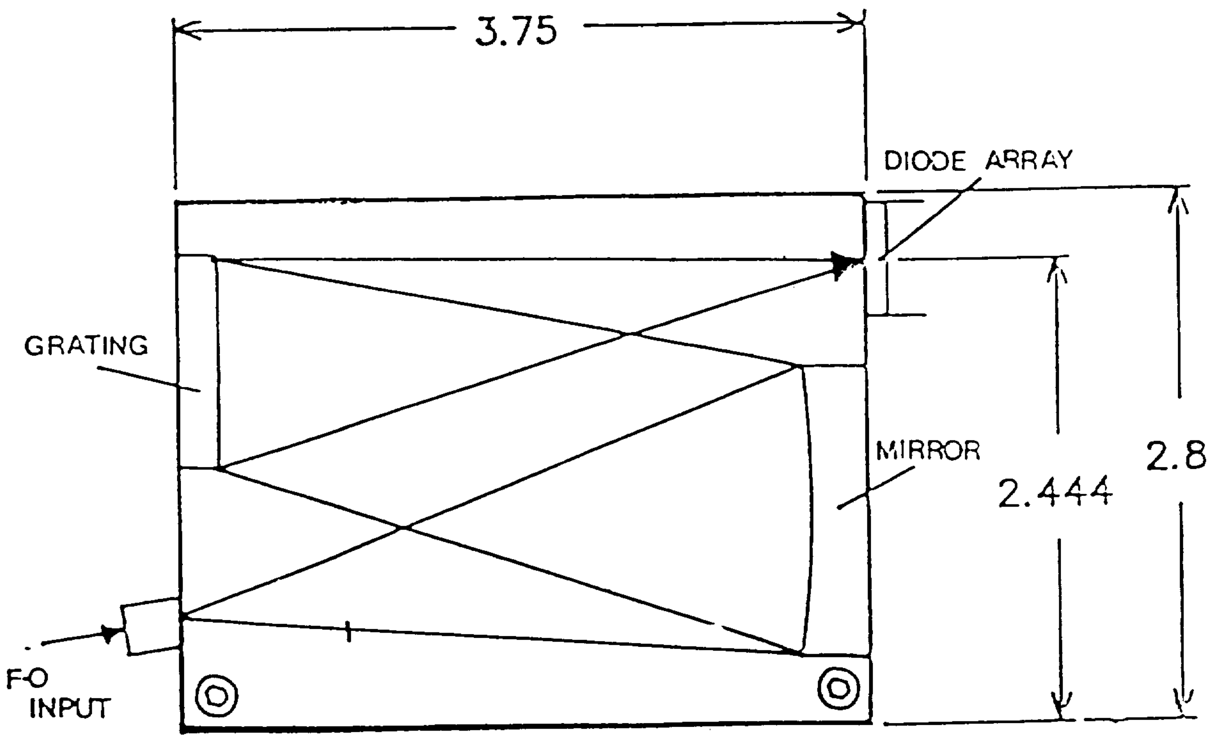

Figure 18.
Fiber Optic Spectrograph Dimensions and Optical Diagram